Use of a Heart Lung Machine in Cardiac Surgery

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Although surgical treatment for heart disease has been available for many years, definitive treatment of intracardiac abnormalities required the development of methods whereby the heart chambers could be entered and lesions treated under direct vision. The first step in this direction was the use of general body hypothermia which reduces the tissue oxygen demand. When the body temperature was reduced to about 28-32°C, the blood flow through the heart could be arrested temporarily and some intracardiac lesions treated. The major drawbacks of this method were: 1) the time limits of the intracardiac procedure (±8 minutes) 2) the ventricular chambers could not be entered without excessive hazard. The successful development of heart lung machines overcame these problems so that the vast majority of cardiac abnormalities are now accessible for definitive surgical treatment under direct vision.

The function of these machines is to divert the venous blood from the inferior and superior vena cava to a device which will oxygenate the blood and remove adequate amounts of carbon dioxide. The arterialized blood is then pumped into the systemic arterial system, usually via the femoral artery. Thus when the heart lung machine is in operation the only blood that enters the heart is from the coronary sinus (into the right atrium) and from the bronchial vessels (into the left atrium via the pulmonary veins). The chambers of the heart can now be opened (cardiotomy) to correct intracardiac defects under direct vision. These procedures are known as open heart surgery during total body perfusion (or cardiopulmonary bypass). The purpose of this paper is to report the results of surgery in 100 consecutive patients in whom the heart lung machine was used for the treatment of congenital heart disease during the last three and one-half years. The role of the anesthetist as a part of the surgical team will be emphasized and the use of monitoring devices stressed.

METHOD

A. Anesthesia

The patients were premedicated with Nembutal®, Demerol® and atropine. The dose of these drugs varied according to the age and weight of the subjects. Adults received about 100 mgms. Demerol®, 0.4 mgms. atropine and 100 mgms. Nembutal®. The dosage schedule for infants and children was as described previously.1

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Originally, induction of anesthesia was started with a small dose of Pentothal Sodium® intravenously (± 50 mgms. of a 2.5% solution) followed by a mixture of nitrous oxide, oxygen and ether using the high liter flow technique. To facilitate endotracheal intubation, transtracheal block with 5% Cyclaine® was used in adults.

In children, open drop ether was given after Pentothal Sodium® induction until anesthesia was deep enough to permit the insertion of an endotracheal tube. More recently the anesthetic agents used were a mixture of Fluothane\textsuperscript{2}, nitrous oxide and oxygen. When premedication was inadequate in children, a sleeping dose of Pentothal Sodium® was given prior to the use of nitrous oxide, oxygen and Fluothane. Ether was added to this mixture prior to endotracheal intubation in some children. The more recent anesthesia technique in adults consisted of induction with Pentothal Sodium® followed by the administration of Fluothane, ether, nitrous oxide (flow of 2 liters per minute) and oxygen (3 liters per minute). Ether was discontinued after endotracheal intubation was accomplished and anesthesia was maintained with low percentages of Fluothane, nitrous oxide and oxygen.

Ventilation was accomplished by augmented respiration until the pleura was entered. At that time Demerol® was given intravenously to abolish the respiratory drive and ventilation was continued using the “hand and bag” method. During the period of total body perfusion the lungs were ventilated with 100% oxygen. Anesthetic gas mixtures were not added to the heart lung machine. In the majority of instances supplemental anesthesia during the period of cardiopulmonary bypass was not necessary. However, a solution of 2.5% Pentothal Sodium® was available at all times and was given into the heart lung machine when indicated. When total body perfusion was discontinued a small percentage of Fluothane was again introduced and respirations controlled until the chest was air tight. Spontaneous respirations were then re-established. Towards the end of the procedure ventilation was assisted with a mechanical respirator to ensure an inspiratory pressure of about 10 cms. water.

Throughout the whole procedure great care was taken to maintain a clear airway to attempt to prevent the onset of acute or prolonged partial hypoxia. This was accomplished by the optimal placement of the endotracheal tube, intermittent aspiration of tracheobronchial secretions and the prevention and treatment of bronchospasm. After the chest incision was closed prophylactic tracheostomy was performed in those patients in whom a stormy postoperative course was predicted. This included patients who had severe pulmonary hypertension, recurrent or recent pneumonitis, or poor risk subjects with severe cardiac malformations. The presence of the tracheostomy tube allowed continued assisted inspiration with a mechanical respirator and a method for adequate aspiration of tracheobronchial secretions in the immediate postoperative period. In the majority of patients tracheostomy was not performed and they were placed in an oxygen tent for 2-3 days after surgery.

B. The Heart Lung Machine

The Clark bubble oxygenator and pump was used in all patients. Details of the apparatus have been published
elsewhere. Venous blood was arterialized with oxygen bubbles of varying size. Small bubbles (10-50 micron) have a large surface and are extremely efficient in oxygenating the blood. The flow of large bubbles (200-500 microns) will remove excess carbon dioxide. The oxygen gas flow was controlled by the arterial oxygen tension and pH (see later). If the oxygen tension fell below the desired level the flow of small bubbles was increased. If the pH fell (i.e. the blood became acidotic) the flow of large bubbles was increased to remove more carbon dioxide. The blood and gas mixture was then allowed to flow over teflon shreds covered with silicone (polymethylsiloxane). This material coalesced the excess gas. The arterialized blood then entered the pumping chamber which was electronically controlled so that the flow rate was known at all times. The blood entered a monitoring chamber before it was returned to the patient. In the latter chamber the oxygen tension, pH and temperature of the blood were measured.

The patients’ venous blood was brought to the heart lung machine via two catheters inserted into the superior and inferior vena cavae. The arterialized blood was returned through a cannula placed in the femoral artery with its tip facing proximally. Thus the blood flow in the aorta was retrograde during the period of perfusion.

The left heart was decompressed in all patients by the insertion of cannulae into the left atrium and left ventricle. The blood from these chambers was aspirated and returned to the heart lung machine. During cardiotomy intracardiac blood was aspirated with hand suckers and returned to the oxygenator. In specific patients the coronary circulation was controlled by occluding the ascending aorta between the origin of the coronary arteries and the innominate artery. In these circumstances viability of the myocardium was protected by stopping the heart beat with coronary perfusion of potassium citrate in the earlier cases and local myocardial hypothermia (± 17°C) in the later patients.

C. Monitoring Devices

1. Systemic Blood Pressure. A blood pressure cuff was attached to the upper arm of all patients. Auscultatory measurements were relied upon only at the beginning and the end of the procedure. In all patients prior to the preparation of the surgical field a peripheral artery, either the radial at the wrist or the brachial at the antecubital fossa was cannulated for the direct measurement of mean arterial pressure. The cannula was attached to a simple mercury manometer. The reference zero point of the manometer was the mid point of the anteroposterior diameter of the chest. (Fig. 1) Pulsations of the mercury column synchronous with the heart beat ensured that the system was open. The cannula was left in situ until the end of the surgical procedure and was removed only when the blood pressure could be measured without difficulty using the auscultatory technique.

2. Venous Pressure. In the first 30 patients of this series, mean venous pressure was measured from both the superior and inferior vena cava. More recently the venous pressure was measured only from the inferior vena cava after this vessel was cannulated from the saphenous vein at the groin. The cannula was attached to a simple water manometer and the reference zero was the mid point of the antero-
posterior diameter of the chest. (Fig. 1) This system was left in situ until the end of the procedure.

3. Temperature. After induction of anesthesia, a thermistor was inserted into the esophagus for the measurement of body temperature. (Fig. 2) The monitoring chamber of the heart lung machine contained another thermistor to measure the temperature of the arterial blood. All of the patients were perfused in normothermia. The extracorporeal blood temperature was controlled by a heating device in the heart lung machine.

4. Electrocardiogram. Needle electrodes were placed subcutaneously for oscilloscopic monitoring of the electrocardiogram. (Fig. 2)

5. Electroencephalogram. Small needles were inserted subcutaneously, one in the frontal area and another in the occipitotemporal area for the oscilloscopic monitoring of the electroencephalogram. (Fig. 2)

6. Arterial Oxygen Tension. The Clark oxygen electrode was used to continuously record the arterial oxygen tension in the heart lung machine prior to the return of the arterial blood to the patient. As indicated above, the level of the arterial oxygen tension was controlled by the flow of small bubbles of oxygen into the heart lung machine. Mixed venous blood was sampled intermittently for oxygen saturation determinations.

7. pH. Electrodes in the monitoring chamber of the heart lung machine measured the pH of the arterial blood. This parameter was recorded continuously during the perfusion. The level of pH was controlled by the flow of large bubbles of oxygen into the heart lung machine.

8. Flow Rate. The pulsatile pumping mechanism of the heart lung machine was controlled electronically. The stroke volume was calibrated prior to each perfusion. Each pump
stroke was recorded as was the number of strokes per minute. Thus the rate of flow of blood from the machine to the patient was known at all times.

9. Blood Volume. The methods of controlling blood volume have been described previously. In summary they depend on the following: (1) the level of the arterial and venous pressures and their relationship to each other (2) blood loss as estimated from sponge weight, discard suction volume, pleural space drainage and loss on the drapes (3) the effects of blood transfusions or the removal of blood from the heart lung machine.

RESULTS

The nature of the congenital lesions and the results of surgery are shown in Fig. 3. The ages of these patients varied from 10 months to 52 years. As indicated, the mortality rate was 14%. Three patients died within 24 hours after surgery and the remainder succumbed within six weeks after perfusion. The commonest cause of death appeared to be related to severe pulmonary hypertension which compli-

DIAGRAMMATIC REPRESENTATION OF TOTAL PERFUSION

Fig. 2 Some of the monitoring devices. (see text)
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Fig. 3 Results of surgical treatment.

cated the congenital defect and antecedced the surgical procedure. There were no deaths which could be attributed to the anesthesia or the heart lung machine.

A representative example of the physiologic control during perfusion is shown in Fig. 4. In the majority of patients a definite fall of the systemic mean arterial pressure was noted soon after occlusion of the vena cavae. The mechanism of the hypotension has been described previously and is probably due to peripheral vasodilation. However, there were no deleterious effects produced by the low blood pressure and in particular, there were no instances of cerebral damage or anuria. Also vasoconstricting drugs were not used. As the perfusion proceeded the mean arterial pressure returned to acceptable levels in the majority of patients, although in some
instances it remained between 45-50 mms. Hg. throughout the intracardiac procedure. When the vena cavae were released and a normal blood volume established, the mean arterial pressure returned to normal. When large volumes of citrated blood were necessary after perfusion, intravenous calcium was given (up to 500 mgms. calcium gluconate for each 500 ml. citrated blood). This therapy invariably produced a salutary effect on the mean arterial pressure. The central venous pressure usually rose during the intracardiac procedure. (Fig. 4) The mechanism of this change has been described previously. In summary the factors involved may include the following (1) relatively small size of venous pickup cannulae (2) malposition of the venous cannulae (3) inadvertent external ab-

**OSTIUM PRIMUM ATRIAL SEPTAL DEFECT**

- **Weight:** 45.9 Kg.
- **Age:** 21 Years.

**Fig. 4** Representative monitoring of physiologic parameters during total body perfusion. (see text)
dominal pressure. In some patients duskeioness of the face was noted with an elevated superior vena caval pressure. This can be prevented by optimal placement of the superior vena cava cannula to prevent partial obstruction of blood flow through this vessel. After excannulation of the vena cavae, the venous pressure usually returned to normal.

The oxygen tension of the arterial blood was maintained at relatively high levels throughout the period of perfusion. (normal $\pm$ 120 mms. Hg.) In the majority of patients the arterial oxygen tension was above 300 mms. Hg. during most of the period of cardiotomy. The relatively high oxygen tension was due to a small volume of oxygen dissolved in the plasma. Bubbles of oxygen were not noted in the arterial blood and there were no instances of oxygen embolism.

The pH of the arterial blood remained within normal limits during the period of perfusion. (Fig. 4) Controlled respiration prior to attachment of the patient to the heart lung machine may result in acidosis from carbon dioxide accumulation or alkalois from over-ventilation. These factors were corrected by varying the volume of large bubble flow into the oxygenator as indicated above. Animal experiments in our laboratories have indicated that a significant metabolic acidosis does not occur during cardiopulmonary bypass so that changes in pH are attributed to carbon dioxide accumulation or loss. Postoperative respiratory acidosis comparable to that reported in patients undergoing thoracotomy for procedures not involving perfusion, may occur but is mild and of short duration.

The rate of flow of arterial blood from the apparatus to the patient varied according to the weight of the patient. In the example shown in Fig. 4 the average flow rate was 2832 ml. per minute (61.7 ml./KG/min. or 2.0 L/M$^2$). Because the saturation of the mixed venous blood remained between 70-75%, it may be assumed that the oxygen requirements of the tissues were supplied adequately.

Blood transfusions during perfusion were necessary in the majority of cases. (Fig. 4) The indications for blood transfusion were one or more of the following: (1) a low and falling mean arterial and central venous pressure (2) “flutter” in the venous pickup line (3) inadequate venous inflow into the heart lung machine when mechanical factors such as kinks in the line or poor placement of the cannulae could be excluded (4) a sudden accidental loss of blood (5) if the mean arterial pressure is not well maintained, although the central venous pressure is normal, transfusion could be considered.

Oscilloscopic visualization of the electrocardiogram was found to be useful throughout the whole procedure. On occasion impending hypoxia was preceded by the development of any arrhythmia, usually ventricular extrasystoles. Complete heart block occurred during cardiotomy in 4 patients with ostium primum atrial septal defect, 2 patients with tetralogy of Fallot and 2 patients with ventricular septal defects. This complication was treated with large doses of intravenous Isuprel® which reverted the heart block to sinus rhythm in 5 instances. One patient succumbed to heart block 1 month after surgery. In 2 instances complete heart block has persisted. The followup period in these latter patients
is 3 years and 18 months. To date the implantation of myocardial electrodes has not been necessary.

Although the electro-encephalogram was visualized oscilloscopically in this group of patients, its value has been dubious. It is believed that deterioration or flattening of the waves of the electro-encephalogram are late manifestations of cerebral damage. Usually the other monitoring devices described above heralded the development of a complication which was overcome prior to significant electroencephalographic changes.

DISCUSSION

Laboratory experience with the heart machine in dogs indicated that successful total body perfusion depended in a great measure on the appreciation of physiologic changes occurring during cardiopulmonary bypass. This experience was transferred to the operating room where the above mentioned monitoring devices were found to be essential in the success of the surgical procedure. We believe that these monitoring devices do not make the operation more complex. In many instances they forewarned the operating room team of impending complications which were not recognized by clinical observation of the patient. These complications were anticipated and controlled before they appeared. The basic principles of total body perfusion depend on optimal oxygenation of blood, removal of adequate amount of carbon dioxide and a flow of blood to meet the metabolic requirements of the body. Therefore it is a fundamental requirement that variation of these parameters be known at all times during total body perfusion.
perfusion. This was accomplished by the monitoring described above.

Fig. 5 represents the personnel of our clinic during surgery with the heart lung machine. They consist of the following groups: (1) operating surgeon, assistants and scrub nurse (2) pump operator, biochemist and scrub nurse (3) anesthetist (4) recorder (5) coordinator. The latter individual acts as a liaison between the other groups. It is his function to advise the pump operating team of changes in the operative field which would influence perfusion techniques in specific patients. Physiologic changes related to anesthesia and blood volume are controlled and treated by the coordinator. He also acts as the direct liaison between the surgeon and the other groups. This system has allowed the surgeon to proceed with the intracardiac procedure without being concerned with the minutia of physiologic and biochemical detail of these major surgical procedures.

SUMMARY

(1) The results of surgery in 100 consecutive patients in whom the Clark heart lung machine was used for the treatment of congenital heart disease is reported.

(2) The role of the anesthetist in these procedures is emphasized.

(3) Monitoring devices to control physiologic and biochemical changes are stressed.

REFERENCES